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ABSTRACT

We report results on the production of muon pairs in the mass range 2.5 to 20 GeV in 400 GeV proton-nucleus collisions. A total of 159 events are observed in the mass range 5.5 to 11 GeV with a cross section which is in agreement with the previous observation of a high mass dielectron continuum signal in this interval. Details on the production dynamics and comparisons with parton model predictions are presented. Within limitations of resolution and continuum uncertainty, the dimuon mass spectrum provides no evidence for fine structure above 5 GeV.

We have previously reported the observation of massive ($\geqslant$ 3 GeV) e^+e^- pairs produced in 400 GeV proton-Be collisions at Fermilab.[1,2] This letter reports the results of an experiment we have performed to detect muon pairs over the same mass range. The conversion to muons was motivated by the higher data taking rate made possible by filtering most hadrons. Although this comes with poorer mass resolution and different backgrounds, we have been able to significantly increase the statistical significance of the high mass data over that in the e^+e^- run.[1]

To carry out these observations, our two arm spectrometer (shown in Fig. 1 of Ref. 1) was modified in a number of ways. Five meters of Be were added as a hadron filter just downstream of the target in the 50-95 mr aperture of each arm. This was followed by 1 m of CH_2. A hodoscope of horizontal scintillators was installed inside each of the spectrometer magnets in order to better define muon trajectories. Two gas Cerenkov counters in each arm provided a high energy threshold for muons of $\sim$ 12 GeV/c. Also, an 8 nuclear mean free path hadron calorimeter was installed behind the lead glass to reject hadrons which punch through the hadron filter. Finally, the muon character of the event was insured by the addition of 1.3 m of steel behind each hadron calorimeter, followed by a set of 3 liquid scintillator muon counters.

It was found necessary to add extensive shielding outside the aperture to protect the detectors against a large flux of very soft muons generated by the hadronic cascade in the Be filter near the target. This background of singles ultimately limited the data rate of the dimuon run. A factor of 8 increase in data taking rate was achieved relative to dielectrons in the high mass range (> 5.5 GeV) permitting a factor of 5 increase in accumulated data between the two experiments.

Data were collected with Cu and Be targets of ~30% of an interaction length using a proton beam intensity of 6 to 9×10^{10} protons per pulse. Backgrounds in the dimuon run arise from several sources: i) muons from pion and kaon decay which contribute to pairs either by accidental coincidences or by correlations of the parent hadrons, and ii) low energy muons which capitalize on the absence of detectors upstream of the magnet and simulate high momentum muons by Coulomb scattering.

A large component of the background was observed and dealt with by studying $\mu^+\mu^+$ and $\mu^-\mu^-$ pairs. About 30% of the running tim was invested in these studies. The same sign pairs are dominated b accidental coincidences (70 ± 30%), as monitored by the technique described in Ref. 1. Since it is known from lower mass dimeson studies[3] that $h^+h^+ + h^-h^- \simeq 2h^+h^-$, a straight subtraction o $\frac{1}{2}(\mu^+\mu^+ + \mu^-\mu^-)$ removes background of type (i) above.[4] Additional background comes from real $\mu^+\mu^-$ pairs at lower mass (e.g. ψ) which, through multiple Coulomb scattering, appear at higher mass. Monte Carlo studies of these effects show that they are negligible above 5 GeV.

Sufficient redundancy in the muon identification was obtained from cuts on track quality χ^2, the correct hodoscope element inside the magnet, Cerenkov pulse heights, the correct muon counter pulse height, and on reconstructed horizontal target location.

Cross sections are obtained using a Monte Carlo calculation of the acceptance which includes the effects of the substantial energy loss of muons in the beryllium and CH_2 absorbers including the contributions of Landau straggling and bremsstrahlung. In the energy determination of the muons, the calculation of Sternheimer[5] for the <u>most probable</u> energy loss has been used. Stringent tests of the Monte Carlo and of this procedure are met by prediction of the observed target distribution and the observed resolution of the J/ψ and of its correctly observed mass value.

The Monte Carlo program calculates an acceptance in the variables m, p_t, $y = 1/2 \ln\left[E^{cm}+p_{\parallel}^{\,cm}\right] / \left[E^{cm} - p_{\parallel}^{\,cm}\right]$ and $\cos\theta^*$ of the dimuon where $\cos\theta^*$ is the decay angle in the dimuon rest frame. A trial model is used to do this and subsequent iteration converges on self-consistent model assumptions and resulting acceptances. We note that the acceptance in y is centered near $y \approx 0$ and ranges from -0.2 to $+0.3$ while the mass acceptance is very broad with sensitivity extending out to 20 GeV.

Figure 1 presents the cross section $d^2\sigma/dmdy$ at $y \approx 0$ versus dimuon mass. An inset also shows a sample of raw data. A total of 159 events are observed above 5.5 GeV mass with Cu target; a strong J/ψ peak and a shoulder consistent with ψ' are also noted.[2] The mass spectrum for $m > 4.5$ GeV is model independent to the level of ± 30% based on the observed distributions of the dynamic variables. In addition, there is an overall uncertainty of ± 40% in the absolute normalization due to uncertainty in flux, efficiency and A-dependence (see below). Our best estimate of the background, obtained from $1/2(\mu^+\mu^+ + \mu^-\mu^-)$ is indicated as the dashed line in Fig. 1.

Figure 2 presents the dynamics of the high mass dimuons. In Fig. 2a we plot the invariant cross section $E\, d^3\sigma/dp^3$ at $y = 0$ versus the transverse momentum, p_t, for each of four mass intervals above 4.5 GeV. As shown by the solid lines in Fig. 2a, the data can be well fit by an exponential form e^{-bp_t} with a mass independent slope parameter $b = 1.29 \pm 0.10$ GeV. Fitting mass intervals separately gives the slope parameters in Table 1. The background is less than 10% in each of these mass bins and has not been subtracted from any of the distributions. We note that these p_t distributions are extremely broad and are in fact characteristic of the trend seen in the production of hadrons.[6]

Figure 2b gives the dependence of the invariant cross section, integrated over p_t, on the center-of-mass rapidity y for the same four mass intervals. The data in each mass interval show no significant y dependence in our narrow range of acceptance ($-0.2 < y < +0.3$). Although we have measured the decay angle distribution in the dimuon rest frame (Gottfried-Jackson frame), the range of our acceptance is so limited ($\cos\theta^* < 0.5$) that discrimination amoung the various polarization states is not possible.[7]

The 360 events on Cu observed with $m > 4.5$ GeV give cross sections $d^2\sigma/dmdy$ at $y \approx 0$ in coarse mass intervals which are given in Table 2 along with the percentage background estimate for each bin. These background subtracted cross sections are plotted in Fig. 3 where they are compared with our electron results[1] and with the predictions of the Drell-Yan parton-antiparton annihilation model[8] employing a variety of parton and antiparton distributions.[9,10,11]

We note further, as in Ref. 1, that all of the parton model predictions require the additional color degree of freedom in order to be consistent with the data integrated over p_t. The parton model of Ref. 10 with $x\bar{u}(x) \propto (1-x)^7$ for the antiparton distribution seems to best characterize the observed mass dependence of the data although it lies yet a factor ~ 1.5 higher in normalization.[7] The effect of the observed broad p_t distributions upon these predictions is not clear to us in these comparisons and raises fundamental questions about the limitations of the Drell-Yan model.[12]

The measured cross section $d^2\sigma/dmdy|_{y=0}$ can be simply parameterized in the scaling form:

$$m^3 \frac{d^2\sigma}{dmdy}\Big|_{y=0} = (3.8\pm1.4)e^{-(15.7\pm1.6)\sqrt{\tau}} \times 10^{-32}\mathrm{cm}^2\mathrm{GeV}^2$$

where $\tau = m^2/s$. This predicts an increase in cross section of a factor of 15 at m = 10 GeV for a cms energy of $\sqrt{s}$ = 52 GeV and it also predicts a cross section greater than $7 \times 10^{-35}\mathrm{cm}^2$ for production of an m = 100 GeV $W^{\pm}$ at $\sqrt{s}$ = 400 GeV.[13]

A separate sample of data with a beryllium target is given in Table 2. It contains 31 events with $m > 5.5$ GeV and, in conjunction with the Cu data, determines the A-dependence in that mass range to be $A^{0.95\pm0.15}$. All cross sections reported here are per nucleon under the assumption of a purely linear A dependence at all masses.

The search for fine structure in a dimuon experiment is hindered by the poor mass resolution (± 2.7% rms) relative to dielectrons. The data do not confirm a possible structure suggested by a clustering of 12 dielectron events near $m_{e^+e^-}$ = 6.0 GeV in the previous experiment.[1,14] We have established the 95% CL upper limit on the cross section for a narrow resonance (i.e. less than the resolution of 380 MeV FWHM at 6 GeV) which can be accommodated by the data to be $d\sigma/dy|_{y=0}\,B = 1.3$ to $2.7 \times 10^{-36}\mathrm{cm}^2$, depending upon assumptions about the continuum shape. This value is only 1/4 to 1/2 of the cross section represented by the clustering in the dielectron experiment. We note that the discrepancy with e^+e^- data could have three origins: i) the electron data are a "one in fifty" statistical fluctuation,

ii) the normalization, A-dependence and resolution differences conspire to obscure the signal in the dimuon data, and iii) least likely, an apparent μe difference is being observed. In forthcoming runs, we hope to double the dielectron data and to increase the muon data by an order of magnitude, while improving the latter resolution by a factor of 1.5.

In summary, we have confirmed our previous observation of a massive dilepton signal above 5 GeV with better statistics and more information on the production dynamics of the continuum signal. In as much detail as we can measure, the data are in gross agreement with a color added parton model except for the unexpected broad transverse momentum behavior.

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REFERENCES

[1] D. C. Hom, et al., Phys. Rev. Lett. 36, 1236 (1976).

[2] H. D. Snyder, et al., Phys. Rev. Lett. 36, 1415 (1976).

[3] D. Bintinger et al., PRL to be published. To the extent that accidentals dominate the background the subtraction method is good to $\leq$ 10% of itself. For correlated hadrons, the relation at lower masses is only good to 20%.

[4] We note that this procedure also subtracts any real same-sign signal whose source could give rise to real $\mu^+\mu^-$ pairs. This corresponds at most to the 30% of the subtraction not accounted for by accidentals, however, and since the subtraction itself is small, the effect is not important. Furthermore, from the point of view of isolating massive dimuon pairs originating from a single parent or virtual gamma, it is a desirable background to subtract.

[5] R. M. Sternheimer and R. F. Peierls, Phys. Rev. B11, 3681, (1971) and R. M. Sternheimer, Phys. Rev. 115, 137 (1959).

[6] Authors who have considered the transverse momentum distributions in the parton model predict a $1/(m_c^2 + p_t^2)^4$ dependence which is consistant with our data for $m_c^2 \simeq 4$. See for example: M. Duong-van, SLAC - PUB - 1604 (1975), and J. F. Gunion, Phys. Rev., to be published.

[7] Results are reported assuming an isotropic decay distribution. However, a $1 + \cos^2\theta^*$ distribution in the Gottfried-Jackson frame would raise all cross sections at high mass by 1.28 while $\sin^2\theta^*$ would reduce them by .69. This constitutes the dominant

model-dependent uncertainty in the cross sections reported.

[8] S. D. Drell and T. M. Yan, Phys. Rev. Lett. 25, 316 (1970).

[9] L. L. Wang, private communication and S. Pakvasa, D. Parasher, S. F. Tuan, Phys. Rev. Lett. 33, 112 (1974).

[10] G. R. Farrar Nucl. Phys. B77, 429 (1974), and J. F. Gunion Phys. Rev. D10 242 (74).

[11] H. P. Paar and E. A. Paschos, Phys. Rev. D10, 1502 (1974) and also J. Bjorken, "most pessimistic form" private communication.

[12] It remains to establish the important scaling predictions of the parton picture and to prove, by a study of high mass μe pairs, the single parent origin of the dileptons. High mass pion-induced events provide another crucial test of the model.

[13] Y. Yamaguchi, Nuovo Cim. 43A, 193 (1966), L. M. Lederman and B. G. Pope, Phys. Rev. Lett. 27, 765 (1971).

[14] Also see D. Eartly, G. Giacomelli, and K. Pretzl, Phys. Rev. Lett. 36, 1355 (1976).

TABLE I

EXPONENTIAL SLOPES IN P_t

m GeV	b $(\mathrm{GeV})^{-1}$	χ^2/DF	< p > (GeV)
4.5 - 5.5	1.26 ± .13	6.5/3	1.59 ± .16
5.5 - 6.5	1.18 ± .24	8.8/3	1.52 ± .19
6.5 - 8.0	1.52 ± .28	2.6/3	
8.0 - 11.0	1.22 ± .39	1.3/3	

TABLE II

HIGH MASS DIMUON CROSS SECTIONS. UPPER LIMITS ARE BASED UPON TWO EVENTS.

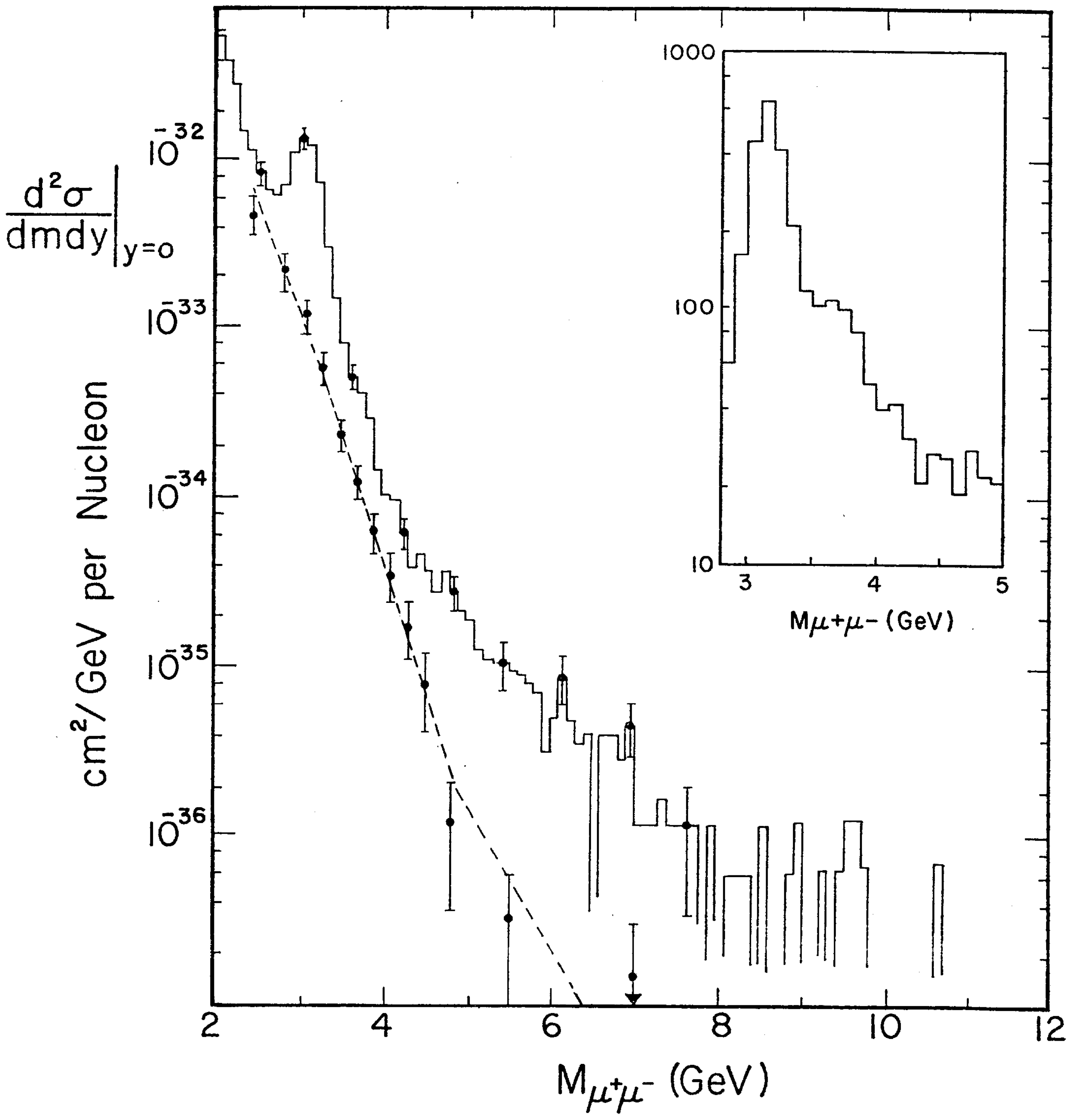
MASS (GeV)	Cu Target (Shown in Figures 1, 2, 3)			Be Target
	Number of Events	Background	$\left.\frac{d^2\sigma}{dmdy}\right\|_{y=0}$ (cm^2/GeV) per nucleon	$\left.\frac{d^2\sigma}{dmdy}\right\|_{y=0}$ (cm^2/GeV) per nucleon
4.5 - 5.0	127	10% ± 5%	$(2.64 \pm .26) \times 10^{-35}$	$(3.66 \pm .66) \times 10^{-35}$
5.0 - 5.5	74	8% ± 8%	$(1.14 \pm .14) \times 10^{-35}$	$(1.67 \pm .38) \times 10^{-35}$
5.5 - 6.0	54	8% ± 8%	$(6.64 \pm .98) \times 10^{-36}$	$(9.98 \pm 2.67) \times 10^{-36}$
6.0 - 6.5	43	< 10%	$(5.12 \pm .78) \times 10^{-36}$	$(2.52 \pm .89) \times 10^{-36}$
6.5 - 7.0	27	"	$(3.07 \pm .59) \times 10^{-36}$	
7.0 - 7.5	11	"	$(1.24 \pm .37) \times 10^{-36}$	$(1.25 \pm .63) \times 10^{-36}$
7.5 - 8.0	8	"	$(9.1 \pm 3.2) \times 10^{-37}$	
8.0 - 9.0	8	"	$(4.7 \pm 1.7) \times 10^{-37}$	$(9.8 \pm 5.7) \times 10^{-37}$
9.0 - 10.0	7	"	$(4.4 \pm 1.7) \times 10^{-37}$	$(1.84 \pm 1.84) \times 10^{-37}$
10.0 - 11.0	1	"	$(6.9 \pm 6.9) \times 10^{-38}$	
11.0 - 13.0	0	-	$< 8.4 \times 10^{-38}$	$(2.46 \pm 2.46) \times 10^{-37}$
13.0 - 15.0	0	-	$< 1.5 \times 10^{-37}$	$< 8.8 \times 10^{-37}$
15.0 - 20.0	0	-	$< 2.2 \times 10^{-37}$	$< 1.5 \times 10^{-36}$

FIGURE CAPTIONS

Figure 1: High Mass Dunuon Spectrum. Errors are statistical only. As in all figures, cross sections are per nucleon with the data from the Cu target only assuming a linear A dependence. Dashed curve is the background obtained from $\frac{1}{2}(\mu^{+}\mu^{+} + \mu^{-}\mu^{-})$. Inset shows the raw data sample at the high mass spectrometer setting.

Figure 2: Dynamics of High Mass Dimuons: a) $E\frac{d^3\sigma}{dp^3}$ at $y \approx 0$. versus p_t for 4 mass intervals (the solid lines represents $e^{-1.29p_t}$) and b) $d^2\sigma/dmdy$ versus y for the same mass intervals. Background has not been subtracted.

Figure 3: High Mass Dilepton Production at 400 GeV. All data is background subtracted and errors are statistical only.



$\frac{d^2\sigma}{dmdy}\Big|_{y=o}$
cm²/GeV per Nucleon
10⁻³²
10⁻³³
10⁻³⁴
10⁻³⁵
10⁻³⁶
2
4
6
8
10
12
Mμ⁺μ⁻ (GeV)
1000
100
10
3
4
5
Mμ+μ- (GeV)

Fig. 1

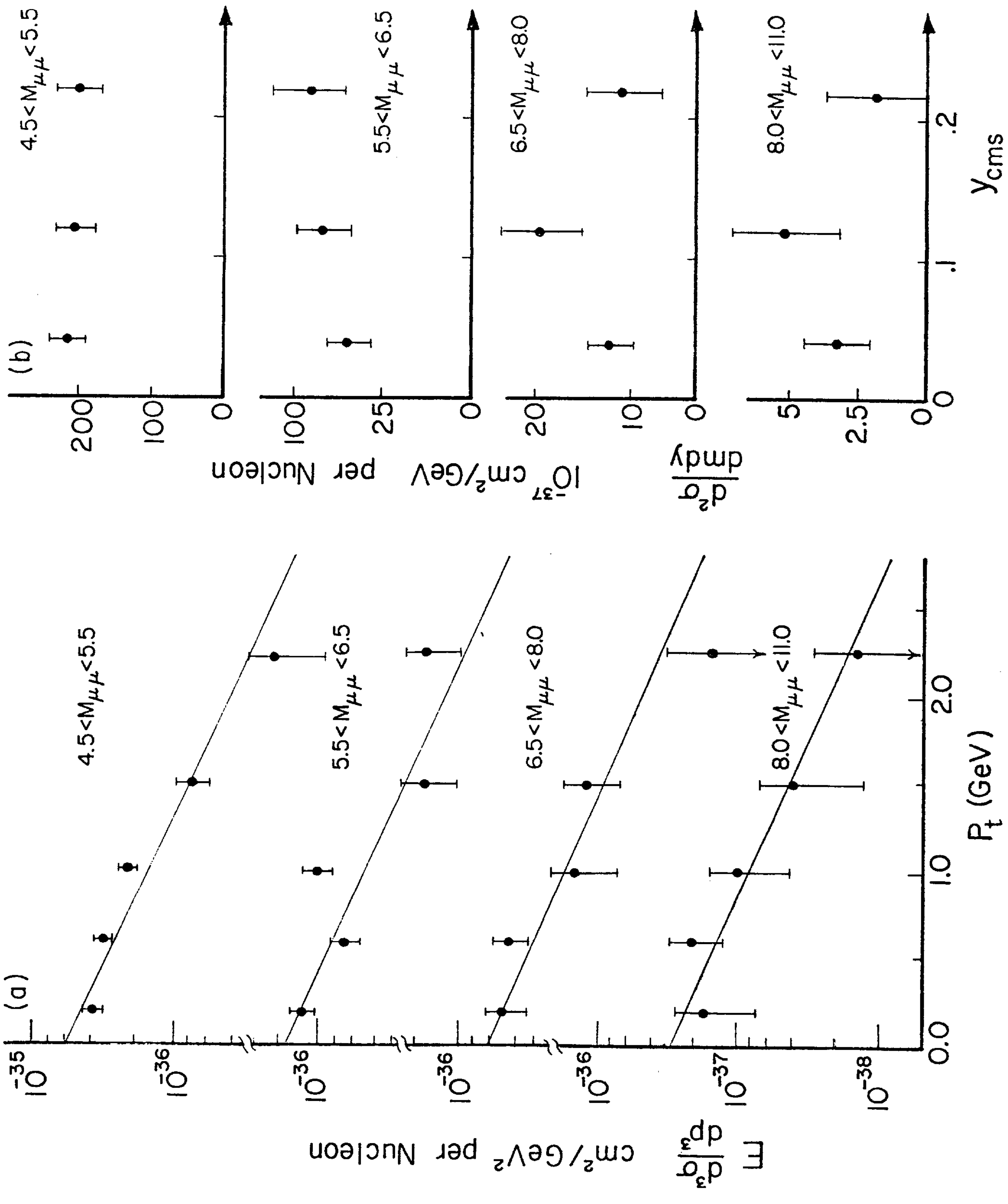

(a)
$4.5<M_{\mu\mu}<5.5$
$5.5<M_{\mu\mu}<6.5$
$6.5<M_{\mu\mu}<8.0$
$8.0<M_{\mu\mu}<11.0$
10^{-35}
10^{-36}
10^{-36}
10^{-36}
10^{-36}
10^{-37}
10^{-38}
$E\frac{d^3\sigma}{dp^3}$ cm^2/GeV^2 per Nucleon
0.0
1.0
2.0
P_t (GeV)
(b)
200
100
0
100
25
0
20
10
0
5
2.5
0
$\frac{d^2\sigma}{dm\,dy}$ 10^{-37} cm^2/GeV per Nucleon
.1
.2
y_{cms}

Fig. 2

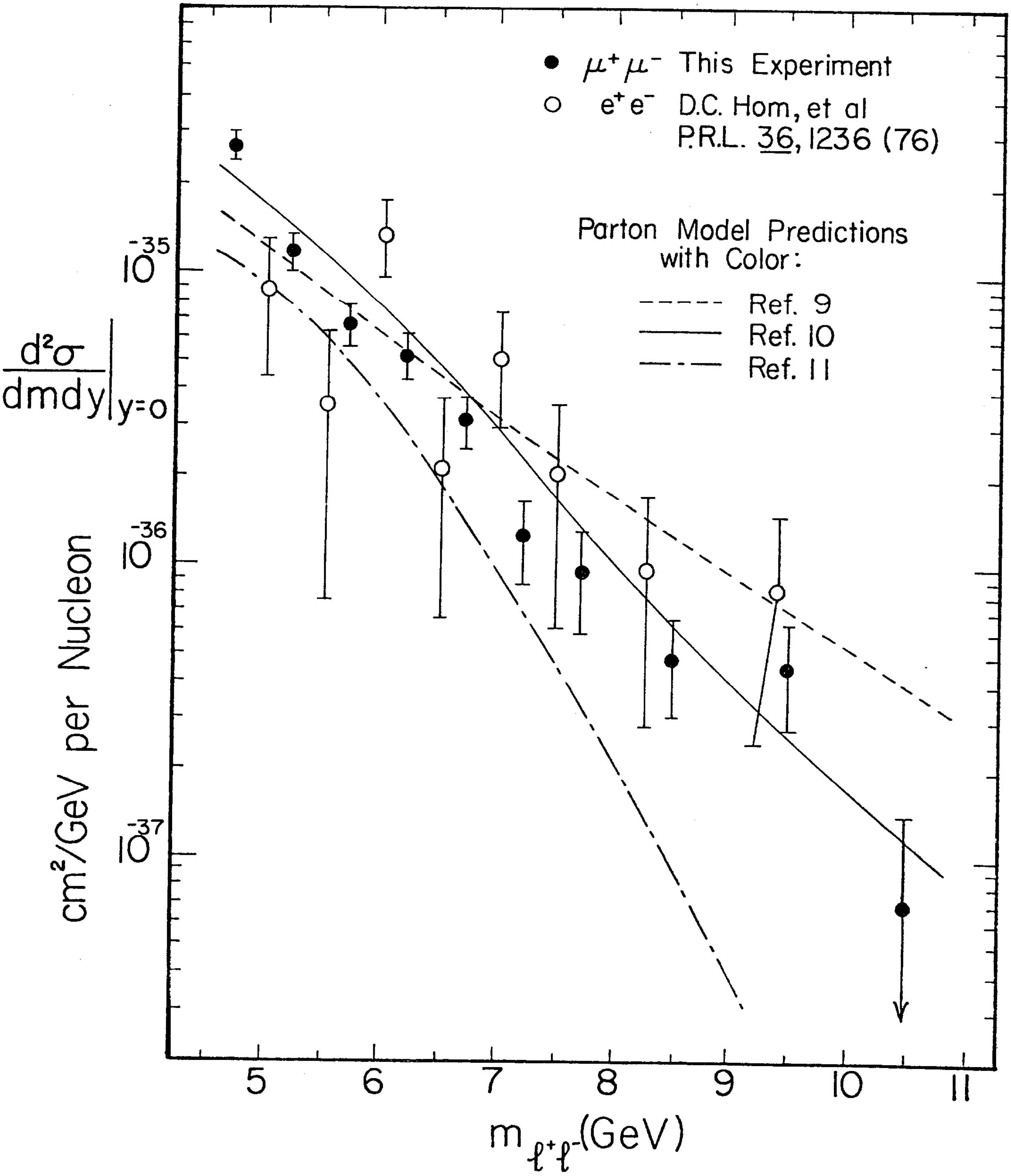

● $\mu^+\mu^-$ This Experiment
○ e^+e^- D.C. Hom, et al P.R.L. 36, 1236 (76)
Parton Model Predictions with Color:
Ref. 9
Ref. 10
Ref. 11
$\left.\frac{d^2\sigma}{dmdy}\right|_{y=0}$
cm²/GeV per Nucleon
10^{-35}
10^{-36}
10^{-37}
5
6
7
8
9
10
11
$m_{\ell^+\ell^-}$(GeV)

Fig. 3